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Recent Developments in Low Voltage FED Phosphors

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Introduction

The low voltage operating conditions of FEDs require a detailed understanding of how the physical and chemical properties of phosphors impact their performance. Lower operating voltages than CRTs result in smaller penetration depths (and volume of excited activators) and reduced luminous efficiency and brightness. This can be compensated by using higher drive currents and taking advantage of the longer pixel dwell time ($x10^3$) of an FED, provided that saturation (due to ground state depletion and thermal quenching) does not limit this approach. The selection of an FED phosphor set must consider all of these factors comprehensively in order to achieve optimization. In this paper, we utilize a simple first order model to predict the brightness saturation behavior of low voltage cathodoluminescent (CL) phosphors, and present data on a series of red, green and blue phosphors. A more complete theoretical model to fit and predict CL properties of phosphors was recently reported in an in-depth analysis of Y_2O_3:Eu.[1]

Recent studies emphasize the need to fully consider the physical and chemical properties of the host lattice, the luminescent activator, and the screening process in selecting and optimizing an FED phosphor. While the screening technologies used are diverse, the properties of the activator and host can be well characterized. The physical attributes of the host lattice (such as electron absorption profile, the multiplication of electrons, the surface and bulk defect recombination, and the electron-hole pair diffusion length), together with the activator control the excitation properties of the material. The principal requirements of the activator center are that it have the correct CIE coordinates and a fast decay time. The latter is essential at high activator concentrations in order for the centers to compete with non-

radiative recombination processes through defects, so that most of the electron-hole pairs recombine radiatively. Otherwise, saturation is likely to occur due to ground state depletion and other energy transfer effects.

Application to Displays

Several factors must be considered when choosing phosphors for FEDs. These include chemical stability in terms of cathode poisoning, degradation of the phosphor under high Coulomb doses, and efficiency/saturation properties. The first issue is dependent upon the cathode structure, but is probably more relevant to the sulfide phosphors. The second issue is interrelated with the cathode poisoning and efficiency issues. Of course, the more efficient the phosphor, the less excitation current is required and the slower the phosphor/cathode degradation.

Assuming a D65 peak white display luminance of 200 cd/m^2, a P22 R:G:B: ratio of 22:71:7, a 25% fill factor for each of the phosphors, and a 50% loss through contrast/color enhancement filters, one obtains required pixel luminances of 350, 1140 and 110 cd/m^2, respectively. The efficiency and saturation properties of a phosphor will determine the current density required to achieve these necessary luminances at a given operating voltage.

Experimental

The efficiency results reported here are intended to be "intrinsic" efficiencies which are not affected by screen issues. Thus, efficiency measurements were obtained on deep powder patches using DC electron gun excitation at current densities $\sim 1 \mu A/cm^2$. The saturation measurements were obtained on phosphors settled (with no binders) on ITO/glass screens at $3 mg/cm^2$. The excitation conditions used for these measurements were 2kV with 30μs pulses at 72Hz to simulate the pixel dwell time for a VGA panel operated at a 72Hz refresh rate. It is important to note that the saturation properties of a phosphor will be sensitive to the excitation pulse width used. The P22 phosphor set and the Tb activated YAG, Y_2SiO_5 and Gd_2O_2S phosphors were obtained from commercial sources while all of the other phosphors were synthesized by the Sarnoff Corporation or the Georgia Institute of Technology under the Phosphor Technology Center of Excellence.

Model

As mentioned previously, the high current density requirements of FEDs can lead to brightness saturation of phosphors due to thermal quenching and ground state depletion. Assuming no thermal effects, one can make a first order estimate of the ground state depletion effects in these phosphors by calculating the number of activators available for excitation. This model simply multiplies the electron penetration depth, the activator concentration and ratio of the pixel dwell time to the activator (1/e) decay time. This last factor accounts for activator recycling.[2] The model neglects electron-hole pair diffusion and concentration quenching, and assumes that the electron beam generation profile is a constant from the phosphor surface to the range of the electrons. Also, no surface effects (dead layer, etc.) are accounted for and no consideration is taken of energy tranfer to noradiative pathways which could enhance saturation properties at the expense of

efficiency. Table 1 lists the relevant parameters and the calculated saturation figure of merit for the phosphors discussed in this paper.

Table 1. Physical parameters of various phosphors and saturation figure of merit as discussed in the text.

Phosphor	Electron Range (nm) @2kV(3)	Dopant Concentration (%)	Decay Time (1/e) (μs)	Satuation Model Figure of Merit
Y_2O_2S:Eu	7.7	3	370	23.1
Y_2O_3:Eu	12	2	1400	24
ZnS:Cu. Al	35	0.01	25	0.42
$SrGa_2S_4$:Eu	5	4	0.5	1200
Gd_2O_2S:Tb	2.8	0.65	470	1.82
YAG:Tb	0.5	2.44	3150	1.22
Y_2SiO_5:Tb	6.2	2	3100	12.4
ZnS:Ag	35	0.01	25	0.42
Y_2SiO_5:Ce	6.2	2	0.025	14880
$SrGa_2S_4$:Ce	5	0.6	0.025	3600

Based on the above figure of merit, the red Y_2O_2S:Eu and Y_2O_3:Eu phosphors should exhibit similar saturation characteristics. For the green phosphors, $SrGa_2S_4$:Eu should have the best saturation followed by Y_2SiO_5:Tb while Gd_2O_2S:Tb and YAG:Tb should have similar but decreased saturation resistance. Finally, ZnS:Cu should exhibit the least saturation resistance. For blue, the Y_2SiO_5:Ce should have the best saturation properties followed by $SrGa_2S_4$:Ce and ZnS:Ag.

Results

Table 2 lists the measured CL properties for the phosphors investigated. These results are discussed below.

Table 2. Measured 2kV CL properties of phosphors including efficiency, CIE coordinates and decay times.

Phosphor	η @2kV (lm/W)	1931 CIE (x,y)	Decay Time to 10% (μs)
Y_2O_2S:Eu	6.0	0.662. 0.332	980
Y_2O_3:Eu	8.9	0.62, 0.35	4100
ZnS:Cu,Al	29.4	0.29, 0.614	160

$SrGa_2S_4$:Eu	49.8	0.232, 0.693	1.24
Gd_2O_2S:Tb	29.2	0.341, 0.562	1400
YAG:Tb	15.3	0.356, 0.542	7800
Y_2SiO_5:Tb	8.4	0.295, 0.461	7100
ZnS:Ag	3.1	0.147, 0.054	120
Y_2SiO_5:Ce	1.0	0.163, 0.071	0.058 (est.)
$SrGa_2S_4$:Ce	5.6	0.135, 0.136	0.058 (est.)

Green Phosphors

In the case of the green phosphors, two projection CRT phosphors, YAG:Tb 2.4% and Y_2SiO_5:Tb 2%, were investigated based on their better saturation properties compared to the standard ZnS:Cu under the high current densities used in projection systems. In addition, two other candidate FED phosphors Gd_2O_2S:Tb 0.65% and $SrGa_2S_4$:Eu 4% were also investigated. Figures 1 and 2 show the luminous efficiencies of these phosphors measured as a function of excitation voltage and current density at 2 kV. From these curves it is shown that the thiogallate exhibits both the best saturation and efficiency while the silicate shows a slightly lower resistance to saturation. The YAG, ZnS and oxysulfide show even lower resistance to saturation, with the YAG and oxysulfide phosphors exhibiting very similar saturation resistance. From these data, the $SrGa_2S_4$:Eu, Y_2SiO_5:Tb, Gd_2O_2S:Tb, YAG:Tb and ZnS:Cu,Al exhibit linear responses (>90% of efficiency under low current density excitation) to average current densities of 20, 15, 6, 5 and 3 $\mu A/cm^2$, respectively.

In general, the experimental data agrees with the model's expectation that phosphors with the larger penetration depths, higher activation concentration and faster activator decay will be more resistant to saturation. The ZnS:Cu exhibits somewhat better saturation properties than expected. This could be due to a relatively large diffusion length which was not accounted for in the model and which would tend to spread out the excitation density.

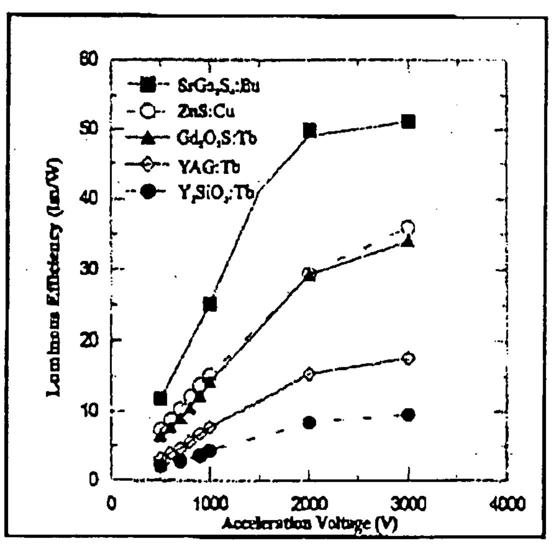

Figure 1. Intrinsic efficiency of candidate green FED phosphors as a function of electron beam energy.

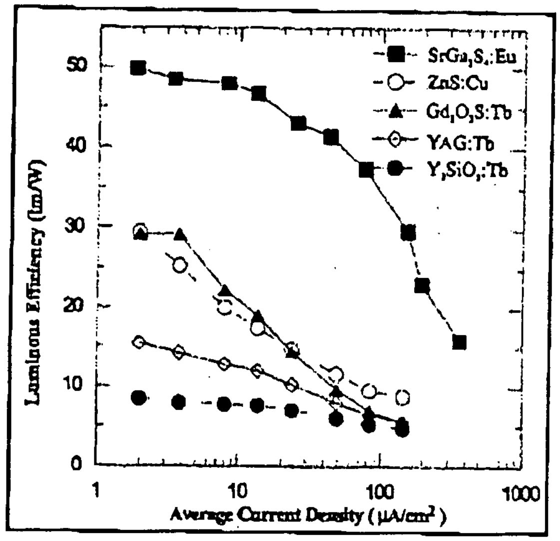

Figure 2. Efficiency of green FED phosphors at 2 kV as a function of average current density.

Blue Phosphors

Figure 3 shows the efficiency results obtained for a standard P22 ZnS:Ag phosphor compared to candidate FED phosphors, Y_2SiO_5:Ce and $SrGa_2S_4$:Ce. As shown in the figure, the P22 exhibits a larger efficiency than the silicate for fairly similar chromaticities, while the thiogallate exhibits the highest efficiency with a less saturated blue emission. However, the Ce activated phosphors were chosen for investigation because of their fast activator, which should provide superior resistance to saturation.. Measurements of the efficiency of these phosphors at 2kV show that the Y_2SiO_5:Ce behaves well to an average current density of ~25μA/cm², while the thiogallate is linear to over 65μA/cm². However, the ZnS:Ag begins to saturate at much lower current densities (~3μA/cm²). Again, these results follow the general trends indicated by the model.

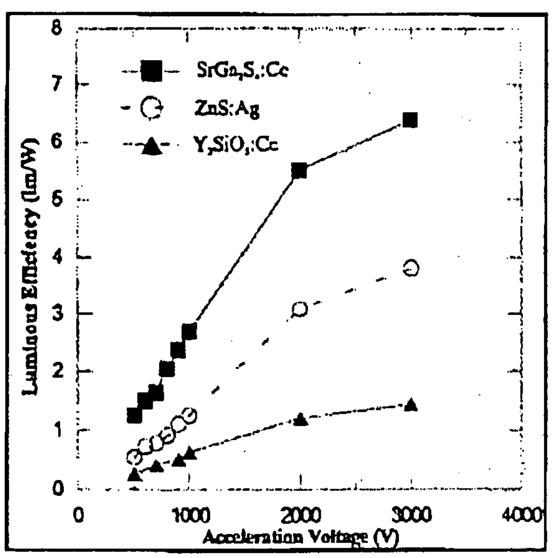

Figure 3. Intrinsic efficiency of candidate blue FED phosphors as a function of electron beam energy.

Red Phosphors

Currently, there is a limited selection of red phosphors for FEDs. Y_2O_3:Eu provides a reasonable efficiency and stability with only a slight shift in chromaticity compared to the P22 Y_2O_2S:Eu. Figure 3 shows the efficiency of Y_2O_3:Eu and Y_2O_2S:Eu as a function of voltage. Of these two phosphors, only the Y_2O_3:Eu saturation properties were measured. It was found that this phosphor exhibits good linearity at current densities up to ~7 μA/cm^2. A similar saturation dependence was assumed for Y_2O_2S:Eu for the calculation of the required current densities outlined below.

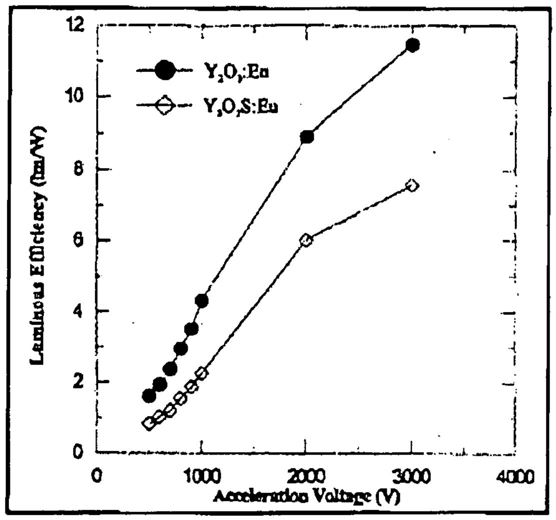

Figure 4. Intrinsic efficiency of candidate red FED phosphors as a function of electron beam energy.

Discussion

Table 3 lists the required average current densities, J, (30μs pulses at 72 Hz) at 2 kV for the phosphors discussed to produce the needed pixel luminances as previously determined assuming that the transmitted luminance is 35% of the total phosphor luminance with no reflected light reaching the viewer. Also included in the table is the normalized efficiency (relative to the nonsaturated efficiencies) of the phosphors at these current densities, and the number of hours of operation to reach an electron dose of 100C/cm^2. It is apparent that at 2 kV, the choices of the phosphors investigated in terms of efficiency are Y_2O_3:Eu, $SrGa_2S_4$:Eu and $SrGa_2S_4$:Ce for red, green and blue, respectively. These phosphors are also the best choices for obtaining maximum life in terms of Coulumb dose. However, the question of phosphor degradation and interaction with the field emission cathodes remains to be determined, especially for the sulfide based phosphors. If the aging of the phosphors is dependent upon the current density and the extent to which the phosphors are saturating then the three choices listed above also meet these criteria. In terms of color saturation, the red and green choices are satisfactory while ZnS:Ag would provide the

best saturated blue. However, the chromaticity of the Ce activated thiogallate can be improved (x=0.64, y=0.09) by modification of the synthesis conditions but at the expense of some efficiency.

Table 3. Average current densities needed to obtain required pixel luminances and the normalized efficiencies and the number of hours to accumulate $100 C/cm^2$ at those current densities (see text for details).

Phosphor	Required Average J @2kV (μA/cm2)	Normalized h at Specified J (%)	Number of Hours to $100\ C/cm^2$
Y_2O_2S:Eu	53 (est.)	50 (est.)	524
Y_2O_3:Eu	29	62	958
ZnS:Cu,Al	42	47	661
$SrGa_2S_4$:Eu	10	95	2777
Gd_2O_2S:Tb	60	30	463
YAG:Tb	78	44	356
Y_2SiO_5:Tb	100	62	278
ZnS:Ag	31	54	896
Y_2SiO_5:Ce	63	80	441
$SrGa_2S_4$:Ce	9	93	3086

Conclusions

The low voltage CL properties of candidate FED phosphors at 2kV are investigated. A simple model for the saturation performance of phosphors is also reported which is in general agreement with experimental results. Based upon efficiency and saturation measurements and the brightness requirements for a 200 cd/m^2 D65 peak white display, an RGB phosphor set of Y_2O_3:Eu, $SrGa_2S_4$:Eu and $SrGa_2S_4$:Ce was selected as a promising candidate for FED displays operating at 2kV. While the actual aging properties of these phosphors and their interaction with field emission cathodes remains to be determined, the thiogallates (especially the green) exhibit remarkable efficiency and saturation properties.

Acknowledgments

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References

1. S. Yang et al., to be published.
2. C. Stoffers et al., J. SID, p. 337, 1996.
3. C. Feldman, Phys. Rev. vol. 117, p. 455, 1960.